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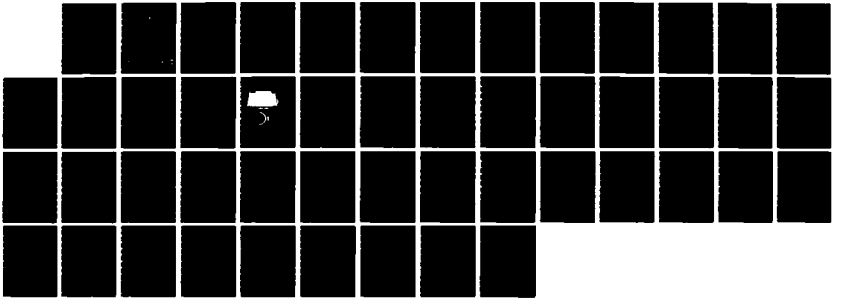

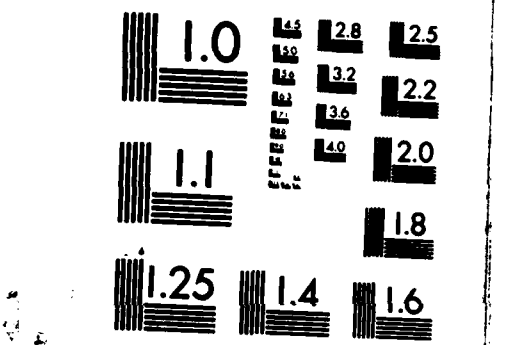

REPORT NO. NADC-81294-60

MEASUREMENT OF HYDROGEN IN HIGH STRENGTH STEELS USING THE BARNACLE ELECTRODE

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JUNE 1983

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for Period 26 May 1982 - 26 May 1983
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The objectives of this program are to demonstrate the effectiveness of the barnacle electrode (BE) for measuring mobile hydrogen and to correlate the levels of such hydrogen with the tendency for delayed failure of two high strength steels, AISI 4340 at the 260-280 ksi (1793-1931 MPa) ultimate strength level and 300M at the 280-300 ksi (1931-2068 MPa) ultimate strength level. These steels were bright cadmium plated to introduce hydrogen into the substrate and then baked for periods of 2 to 100 hours. The notch stress rupture stress to produce failure in 200 hours was used to measure susceptibility to hydrogen embrittlement.

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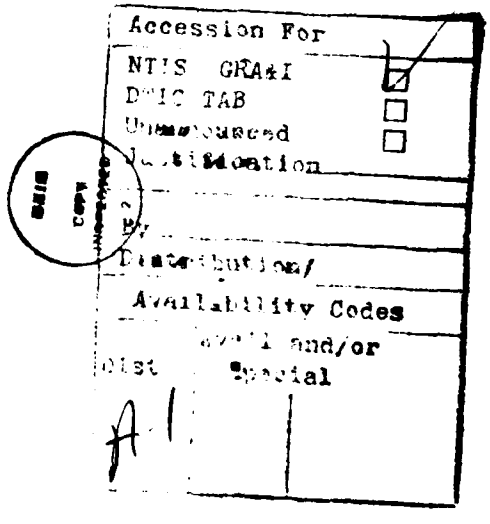
The results indicate that the BE can effectively measure mobile hydrogen and susceptibility to delayed failure can be correlated with BE measurements. Confidence in the use of the BE system can be increased by delineating the cause for the observed variation in current density readings.

NADC-81294-60

FOREWORD

This final report summarizes the work performed during the period May 1982 to May 1983 for contract N62269-82-C-0231 under the technical direction of Dr. David Berman, Naval Air Development Center, Warminster, Pennsylvania.

The program was conducted by the McDonnell Aircraft Company, with H. C. Turner as Program Manager, R. J. Kotfila as Principal Investigator and H. M. Keeser as Laboratory Investigator.



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1. INTRODUCTION

Delayed failures of high strenyth steels can result from hydroyen generated by in-service corrosion or absorbed during pickling and electroplating processes. The use of corrosion prevention systems minimizes corrosion-related embrittlement. Hydroyen pickup duriny fabrication is controlled by the use of low-embrittlement electroplates, avoidance of hydroyen-producing solutions and bakiny to reduce the hydroyen. The effectiveness of these controls is measured by mechanical tests, such as tensile notch stress rupture, stress rings and bend specimens with pass-fail criteria of load-time established for each test method.

The mechanical tests to measure the embrittling effects of hydroyen were necessary because of a lack of an acceptable method of hydroyen analysis. Hydroyen can exist in two forms: trapped and mobile. Most methods of hydroyen analysis measure total hydroyen. However, the bulk of this hydroyen is in the form of trapped hydroyen which is considered nondiffusible and innocuous in the embrittliny mechanism. Of prime importance is the level of mobile hydroyen because it is the primary source of the embrittliny species leading to the delayed failure of high strenyth steel. Mobile hydroyen lower than 0.2 ppm can lead to embrittlement of a steel thouyh its total hydroyen content is 2 ppm or yreater (Reference 1). Reliable direct measurement of mobile hydroyen levels in steels was difficult until the development of the Barnacle Electrode (BE) (References 2, 3, 4 and 5). This instrument measures mobile hydroyen by usiny the principle of electrochemical oxidation of diffusible evolviny hydroyen.

The objectives of this proyram were to demonstrate the effectiveness of the barnacle electrode for measuriny mobile hydroyen and to correlate the levels of such hydroyen with the tendency for delayed failure of two hiyh strength steels, AISI 4340 at 260-280 ksi (1793-1931 MPa) ultimate strenyth level and 300M at the 280-300 ksi (1931-2068 MPa) ultimate strength level. These steels were cadmium plated to introduce hydroyen into the substrate and then baked for periods of two to 100 hours to vary the hydroyen levels. The notch stress rupture stress to produce failure in 200 hours was used to measure susceptibility to hydroyen embrittlement.

The program plan to achieve these objectives is shown in Fiyure 1.

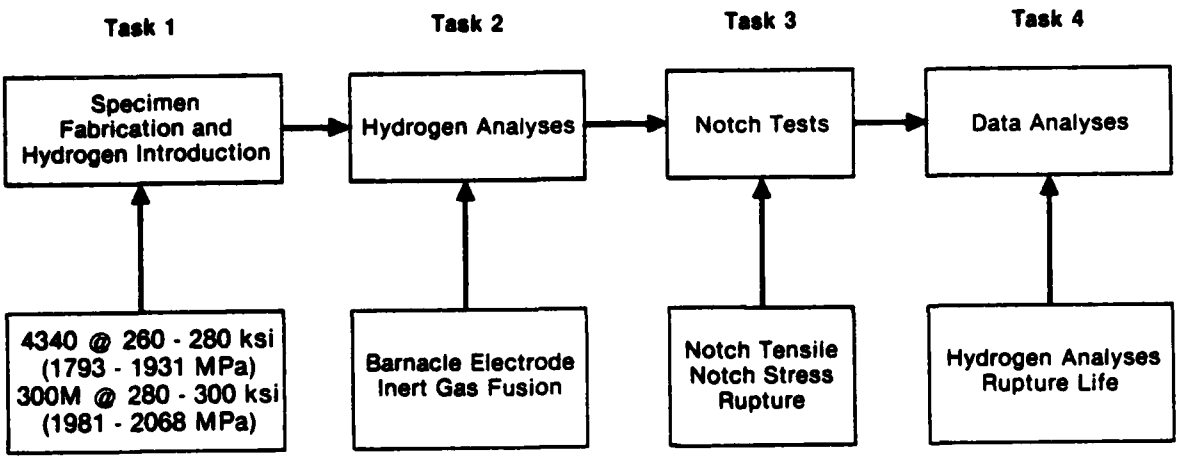

Figure 1. Program Plan

2.0 SUMMARY

Flat notch stress rupture specimens were machined from AISI 4340 and 300M steels, and heat treated to 260-280/ksi (1793-1931 MPa) and 280-300 ksi (1931-2068 MPa), respectively. Hydrogen was introduced into specimens by bright cadmium plating; the levels of hydrogen were varied by baking at 375°F (190°C) for times between 2 and 100 hours.

Mobile hydrogen was measured using the barnacle electrode (BE) system. The mobile hydrogen content decreased with increasing bake time with the most significant decreases occurring after bake times of 24 hours and longer. A 100 hour bake time was required to obtain approximate baseline (unplated) mobile hydrogen values. There was a significant variation in BE readings within a specimen and between specimens from a specific bake cycle.

Total hydrogen was measured using the inert gas fusion method. Fluctuations were observed in total hydrogen content as a function of bake time. This was attributed to entrapped hydrogen in the cadmium plate which diffused into the steel during baking. No correlation was observed between mobile and total hydrogen.

The threshold stress for the 200 hour notch stress rupture life was used to measure susceptibility to delayed failure due to hydrogen embrittlement. Decreasing amounts of mobile hydrogen resulted in higher threshold stresses (as measured by percent of notch tensile strength) for 200 hour safe life indicating correlation between the measured BE readings and propensity to delayed failure. A more complete correlation could have been obtained if a larger range of bake cycles were used.

A data summary is presented in Table 1.

TABLE 1
DATA SUMMARY

Condition, Plated and baked at 375°F (190°C) for hours indicated	Average BE Reading μ A/cm^2		Average Total Hydrogen Content, ppm		Threshold Stress, % NTS	
	4340	300M	4340	300M	4340	300M
0	0.83	0.80	1.54	-	15	-
2	0.76	-	1.68	-	20	-
4	0.78	-	2.65	1.87	20	20
12	0.74	0.66	2.32	1.50	20	20
24	0.63	0.63	1.72	1.27	30	20
72	0.60	0.48	2.10	1.44	45	-
100	-	0.38	-	-	-	65
Baseline - unplated	0.39	0.40	1.20	1.86	90	90

The results of this investigation show that mobile hydrogen as measured by the BE is a better indicator of hydrogen embrittlement than the total hydrogen content measured by inert gas fusion. Mobile hydrogen contents as low as 0.15 ppm equivalent to a BE reading of 0.8 μA/cm^2 are sufficient to reduce the threshold stress for 200 hour notch stress rupture life to only 15% of its baseline notch tensile strength.

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3. RESULTS

The details for the four tasks conducted in this program and the results of each task are described in the following sections.

3.1 TASK 1 - SPECIMEN PREPARATION AND HYDROGEN INTRODUCTION - The materials and strength levels tested were AISI 4340 (Mil-S-5000) at 260-280 ksi (1793-1931 MPa) ultimate tensile strength level and 300M (AMS 6419) at 280-300 ksi (1931-2068 MPa) ultimate tensile strength. AISI 4340 was selected because it is highly susceptible to hydrogen embrittlement (HE) at high strength levels and it was used extensively in previous HE studies. The 300M steel is a primary material for aircraft landing gears and delayed failures due to HE is a potential problem.

The steels were analyzed for conformance to specification composition requirements and the results are shown in Table 2. The tramp elements were included in the analyses in the event any unusual or anomalous behavior between the two steels were uncovered in subsequent tests.

TABLE 2. COMPOSITION OF AISI 4340 AND 300M STEEL SPECIMENS

Element	AISI 4340		300M	
	Actual	MIL-S-5000	Actual	AMS 6419
Carbon	0.41	0.38/0.43	0.43	0.40/0.45
Manganese	0.71	0.65/0.85	0.74	0.60/0.90
Phosphorus	<0.015	0.025 Max	<0.015	0.010 Max
Sulfur	0.014	0.025 Max	0.005	0.01 Max
Silicon	0.24	0.15/0.30	1.58	1.45/1.80
Nickel	1.65	1.65/2.00	1.71	1.65/2.00
Chromium	0.82	0.70/0.90	0.76	0.70/0.95
Molybdenum	0.25	0.20/0.30	0.35	0.30/0.50
Aluminum	0.035	—	0.081	—
Vanadium	0.003	—	0.06	0.05/0.10
Copper	0.21	—	0.17	0.35 Max
Titanium	0.004	—	0.01	—
Boron	<0.001	—	<0.001	—
Arsenic	<0.01	—	<0.01	—
Zirconium	<0.01	—	<0.01	—
Cobalt	0.033	—	0.023	—
Niobium	<0.005	—	<0.005	—
Tin	<0.020	—	<0.02	—
Antimony	<0.010	—	<0.01	—

Flat notch stress rupture (NSR) specimens, shown in Figure 2, were used to measure the effect of hydrogen on delayed failure. The large flat surfaces permitted BE readings directly on the specimens without the need for electrodes of special geometry.

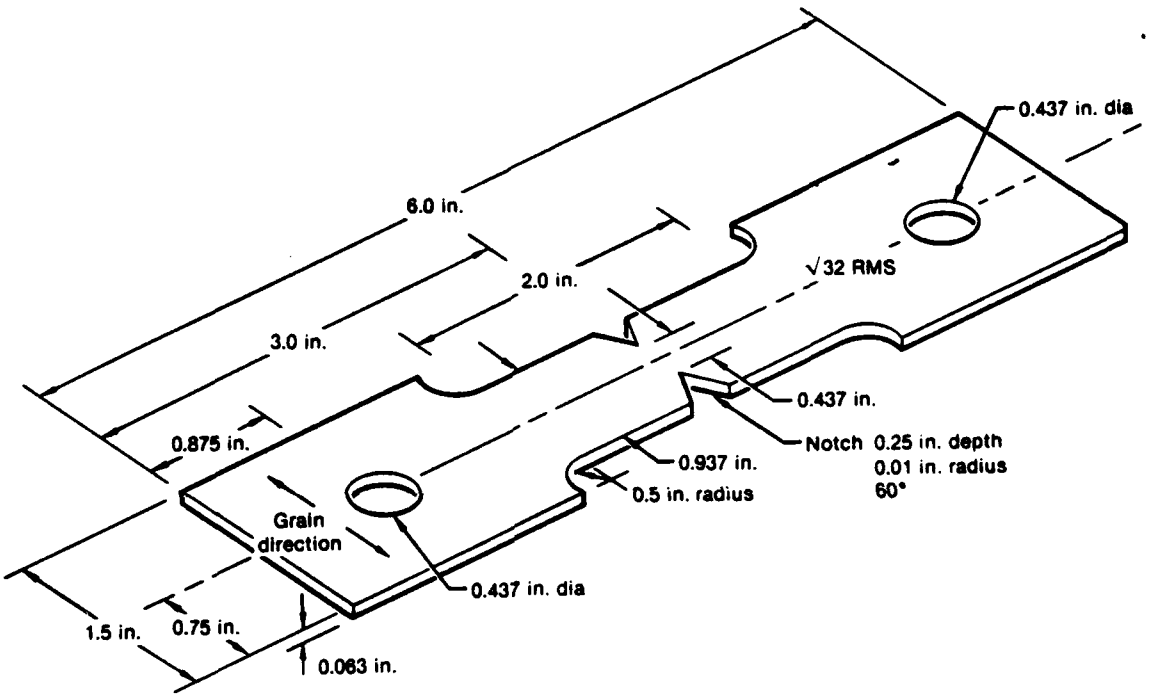


Figure 2. Notch Specimen

Witness coupons, 0.063" x 1" x 6" (1.6 x 25 x 150mm) were made from the same heats of material. One or more coupons were plated and baked with each batch of NSR specimens to determine hydrogen pickup after each plating run.

The NSR specimens and witness coupons were heat treated to the stated strength levels according to Mil-H-6875. Each specimen was then hardness tested to assure proper heat treatment. The specimens and the coupons were then ground flat and the notches crush ground. The notches were measured for conformity to print using a precision optical comparator. All specimens were within print requirements. An ammonium persulfate etch test of the notch areas revealed no evidence of grinding burns.

All specimens and coupons were baked for 2 hours to remove any hydrogen picked up during processing. The specimens were packed in polyethylene bags and stored in a dessicator until plated.

The specimens were bright cadmium plated per QQ-P-416 using the following conditions:

NaCN - 15 oz/gal (112.4g/l)

CdO - 3.5 oz/gal (26.2g/l)

NaOH - 2.3 oz/gal (17.2g/l)

Brightener - 0.75 oz/gal (5.6g/l)

Current Density - 20 Amps/sq. ft. (215 Amp/m^2)

All specimens were plated in lots with five NSR specimens and one witness coupon in a lot. After plating, the 4340 specimens were baked at 375°F (190°C) for 2, 4, 12, 24 and 72 hours; the 300M specimens, at 4, 12, 24 72 and 100 hours. The decision to eliminate the 2 hour bake and substitute the 100 hour bake for the 300M steel was based on the results obtained on the 4340 steel.

3.2 TASK 2 - HYDROGEN ANALYSES - Barnacle electrode readings were made on one or more witness coupons and on the specimens after notch stress rupture testing. Inert gas fusion analyses were made on witness coupons only.

3.2.1 Barnacle Electrode Readings - The principle of operation of the BE, described in detail in References 2 and 3, is based on an electrochemical cell in which a nickel/nickel oxide electrode in an alkaline electrolyte maintains zero hydrogen concentration at the surface of the steel by oxidizing the emerging hydrogen atoms to water. The current density at any given time, can be related to the hydrogen concentration according to the equation:

$$\frac{J}{ZF} = C_o \left(\frac{D}{\pi t}\right)^{1/2} \qquad \text{(Equation 1)}$$

where Z = number of electrons involved in the oxidation

F = Faraday's constant, 96,500C/mol

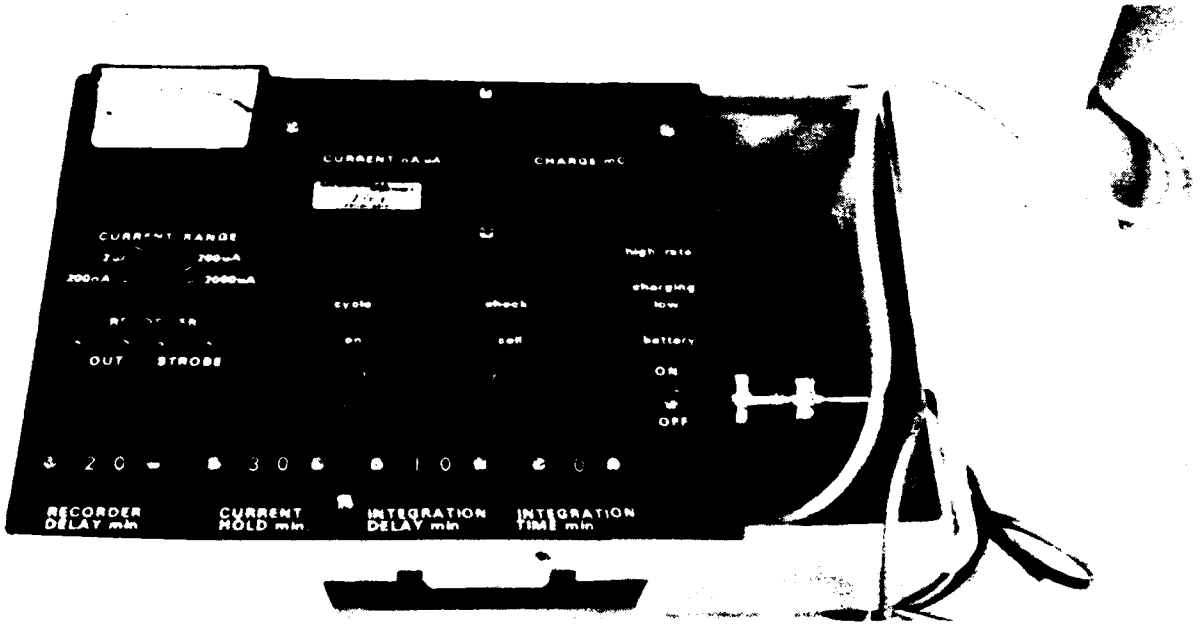
C_o = uniform hydrogen concentration, mol/cm^3

D = diffusivity of hydrogen through steel, cm^2/sec

J = permeation current density, amps/cm^2

t = time seconds

A photo and schematic of the barnacle electrode system is shown in Figure 3.



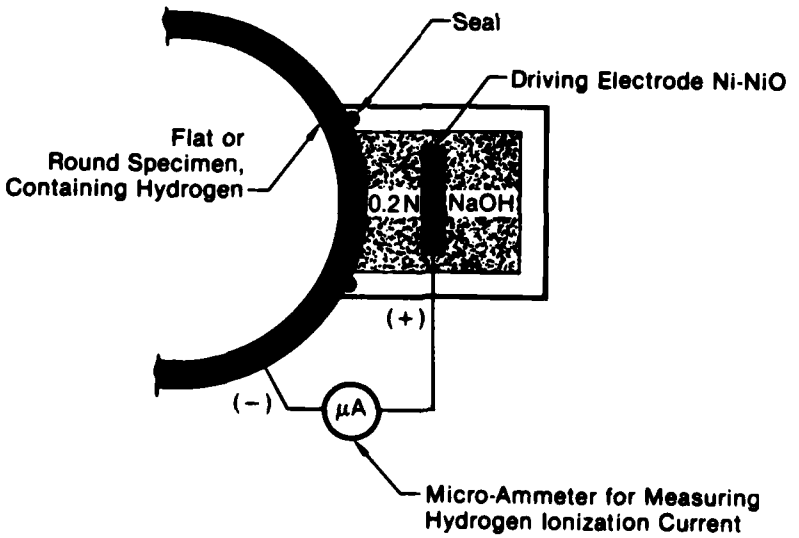


Figure 3. Barnacle Electrode System

In lieu of the maynetic barnacle, a machinist vise was used to maintain a leak-free joint between the teflon cell and the test specimen. The procedure used for making BE readings is as follows:

1. Chemically strip the cadmium plate from one side usiny an ammonium nitrate solution (1 lb/yal - 120 ym/l).
2. Examine surface visually for complete removal of platiny.
3. Rinse with methanol and dry.
4. Abrade lightly with abrasive pads.
5. Methanol wipe and dry with clean paper towels.

Immediately after drying, the specimen was loaded ayainst the cell and clamped in a machinist's vise to obtain a leak free joint. Fresh electrolyte (0.2N NaOH) was added to the cell, hand vibrated to eliminate any entrapped air bubbles, and then the cell was turned on. Readiny were taken after 30 minutes.

The instrument and the electrode were calibrated at frequent intervals to assure proper readouts and voltayes.

Specimen surface smoothness, and cell gasket condition influence accuracy and reproducibility of analyses. Both of these factors affect surface area, which is assumed to be 1 cm^2 for all readiny. To minimize the influence of these variables, the surface smoothness of the specimen and witness coupon was maintained at 32 RHR; the cell gasket was checked frequently for resilience and edye condition and, when necessary, it was replaced with a freshly cut gasket.

Summaries of the BE readings are contained in Tables 3 and 4. Individual readings are contained in the appropriate tables in the Appendix. A statistical analysis was made to determine the mean ($\bar{x}$) and the standard deviation (s) of the BE readiny. The results are plotted in Fiyures 4 and 5 for the 434U and 300M steels, respectively.

TABLE 3

DATA SUMMARY
BARNACLE READINGS AND TOTAL HYDROGEN CONTENT
AISI 434U STEEL

BARNACLE READINGS	BASELINE (UNPLATED)	PLATED, BAKE TIME HOURS					
		0	2	4	12	24	72
$\bar{x}$, $\mu A/cm^2$	0.39	0.83	0.76	0.78	0.74	0.63	0.60
s, $\mu A/cm^2$	0.06	0.11	0.08	0.17	0.07	0.10	0.09
n, Number of specimens	23	6	4	7	5	6	4
TOTAL HYDROGEN							
Average ppm	1.20	1.54	1.68	2.65	2.32	1.72	2.10
Number of specimens	3	2	1	1	1	1	1

TABLE 4

DATA SUMMARY
BARNACLE READINGS AND TOTAL HYDROGEN CONTENT
300M STEEL

BARBACKE READINGS	BASELINE (UNPLATED)	PLATED, BAKE TIME HOURS 4	12	24	72	100
$\bar{x}$, $\mu A/cm^2$	0.41	0.80	0.66	0.63	0.48	.38
s, $\mu A/cm^2$	0.05	0.10	0.13	0.06	0.06	.04
n, Number of specimens	15	4	5	4	6	3
TOTAL HYDROGEN						
Average, ppm	1.86	1.87	1.50	1.27	1.44	-
Number of specimens	2	1	1	1	1	-

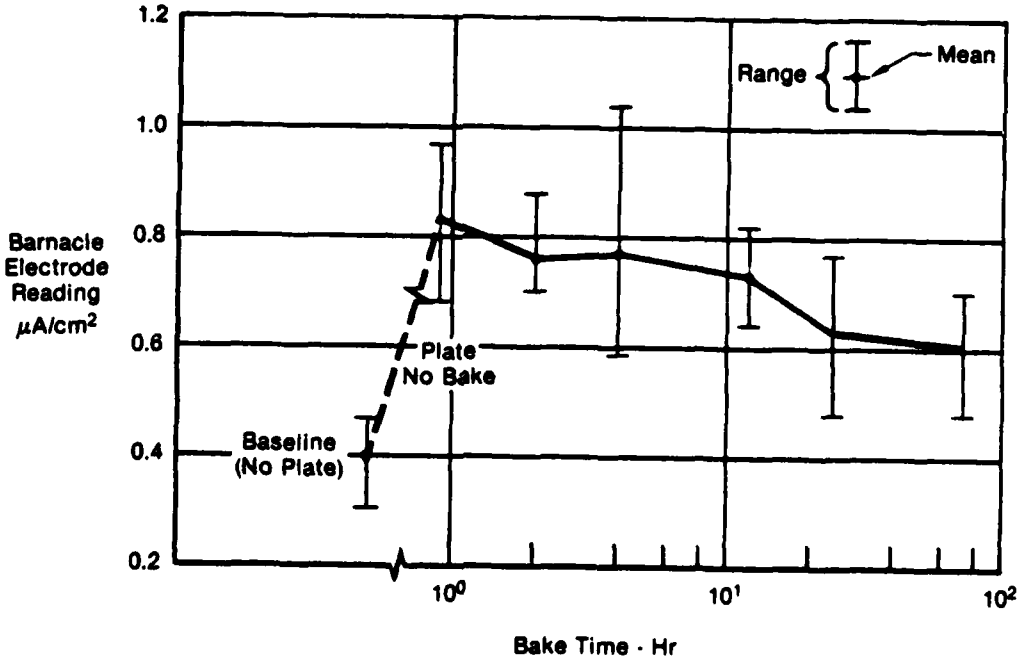


Figure 4. Effect of Bake Time on BE Measurements of Bright Cadmium Plated 4340 Steel

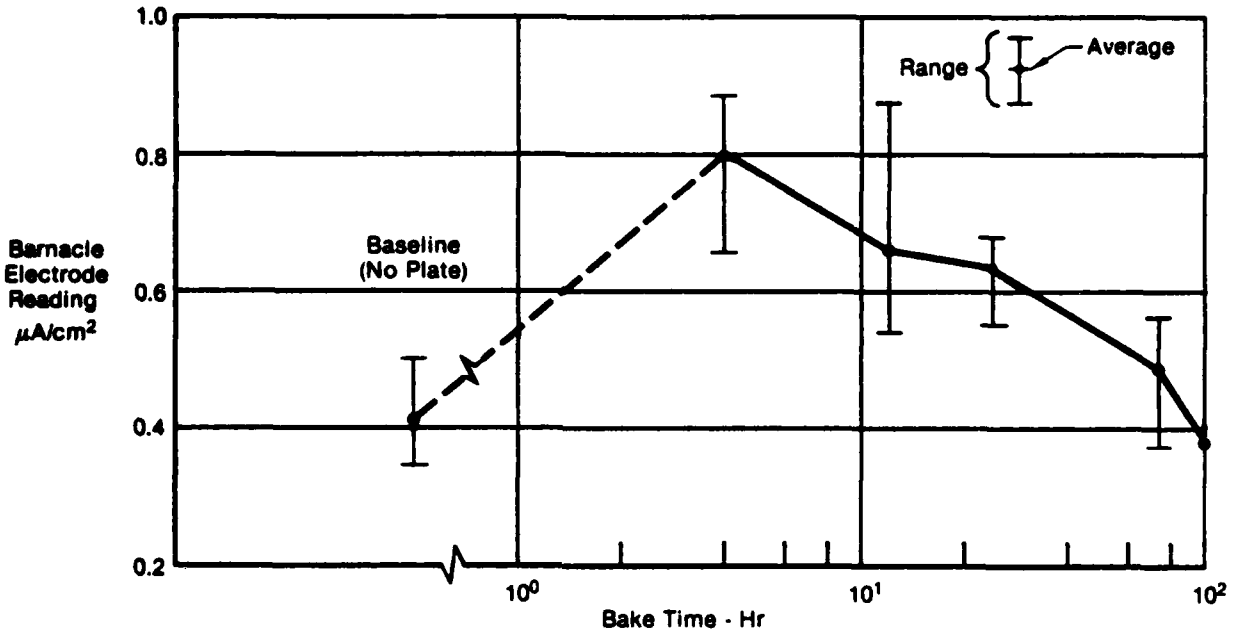


Figure 5. Effect of Bake Time on BE Measurements of Bright Cadmium Plated 300M Steel

The cause for variations observed in the BE readings of the unplated specimens could not be determined. The magnitude of the baseline values is higher than that observed by Berman (Reference 6). Although an occasional high or low value was obtained within a specimen, the greatest variation was observed between specimens. This variation may be the result of incipient corrosion which may have occurred during the period between machining and testing - although care was exercised to prevent this by storing the specimens in dessicator. No evidence of corrosion was observed under close visual examination.

The variation in the plated and baked specimens is probably due in part to localized grain boundary diffusion of hydrogen present in the plate. The plate as a source of hydrogen is discussed in the succeeding section. Another cause for variation may be hydrogen diffusion into the specimen gauge section during the notch stress rupture testing. Berman observed differences in mobile hydrogen content in specimen gauge sections before and after NSR testing (Reference 7). Although this was also observed only in some instances in this study, the conditions of testing (percent load and time at load) was not uniform for all specimens and therefore some variations in BE readings from specimen to specimen would be expected here.

Despite the observed variations, there was a definite trend toward lower mobile hydrogen contents with increasing bake time. However, a 100 hour bake was required to reduce the amount of mobile hydrogen to baseline values for the 300M steel.

3.2.2 Inert Gas Fusion - This analysis was performed using a Leco RH2 analyzer. This instrument measures the total hydrogen which outgasses from a fused sample. The thermal conductivity of nitrogen (carrier gas) and hydrogen, which is released during fusion of the sample, is measured and related to a known hydrogen content. Standards, supplied by the National Bureau of Standards in lieu of dosing with hydrogen gas, were used to check the analyses.

The inert gas fusion analyses were made on one or more witness coupons only. Samples for inert gas fusion analyses were cut from the coupon and the balance of the coupon was used for BE analyses. This permitted a direct comparison of the two forms of hydrogen, mobile and total, from the same specimen. An effort was made to run both analyses concurrently to eliminate time (which may allow outgassing) as a variable. Cadmium plating when present, was stripped with ammonium nitrate, and the coupons rinsed and dried. The analysis was performed as soon as practicable after stripping of the plate.

A summary of the total hydrogen measurements is also shown in Tables 3 and 4 (individual readings are contained in appropriate tables in the Appendix). The data show a small increase in total hydrogen after plating, after plating and baking 2 hours, and a significant increase after baking 4 hours. Increasing the bake over 4 hours, reduced the total hydrogen. This initial increase in total hydrogen content can be attributed to diffusion of hydrogen from the cadmium plate. The plate can be a source of large amounts of hydrogen. For example, a nickel plate was found to contain 180 times more hydrogen than the substrate (Reference 1). This type of concentration gradient would promote diffusion of hydrogen into the substrate as well as to the atmosphere.

3.2.3 Comparison of Total Hydrogen and Mobile Hydrogen - A comparison of mobile and total hydrogen contents are shown in Figures 6 and 7. The mobile hydrogen content was calculated using Equation (1) with $D = 4.5 \times 10^{-7}$ cm^2/sec for the 300M and $2.5 \times 10^{-7} cm^2/sec$ for the 4340 steel (References 3 & 8). The results were converted to parts per million (ppm) to permit direct comparison. The calculated mobile hydrogen contents for the baseline for both steels are invalid as they are primarily background measurements. The values are presented here only to indicate a potential lower limit of mobile hydrogen. Although a decrease in mobile hydrogen is observed with increasing bake time, a similar trend is not evident in the total hydrogen content and therefore a correlation between these two values after a specific bake cycle cannot be made.

3.3 TASK 3 - NOTCH TESTS

3.3.1 Notch Tensile Strength (NTS) - Ten specimens of each steel were tensile tested to determine the notch tensile strength. The average notch tensile strength for the 4340 steel was 268 ksi (1848 MPa) and for the 300M steel was 313 ksi (2158 MPa). These values were used to establish the stresses for the 200 hour notch stress rupture tests.

3.3.2 Notch Stress Ruputure (NSR) Tests - The notch stress rupture tests were performed according to ASTM E292 using two Arcweld creep frames, Model JE. These frames, dedicated to room temperature testing, use a yoke and pin gripping arrangement. Before the tests were initiated, the load train was checked for alignment and no misalignment was detected.

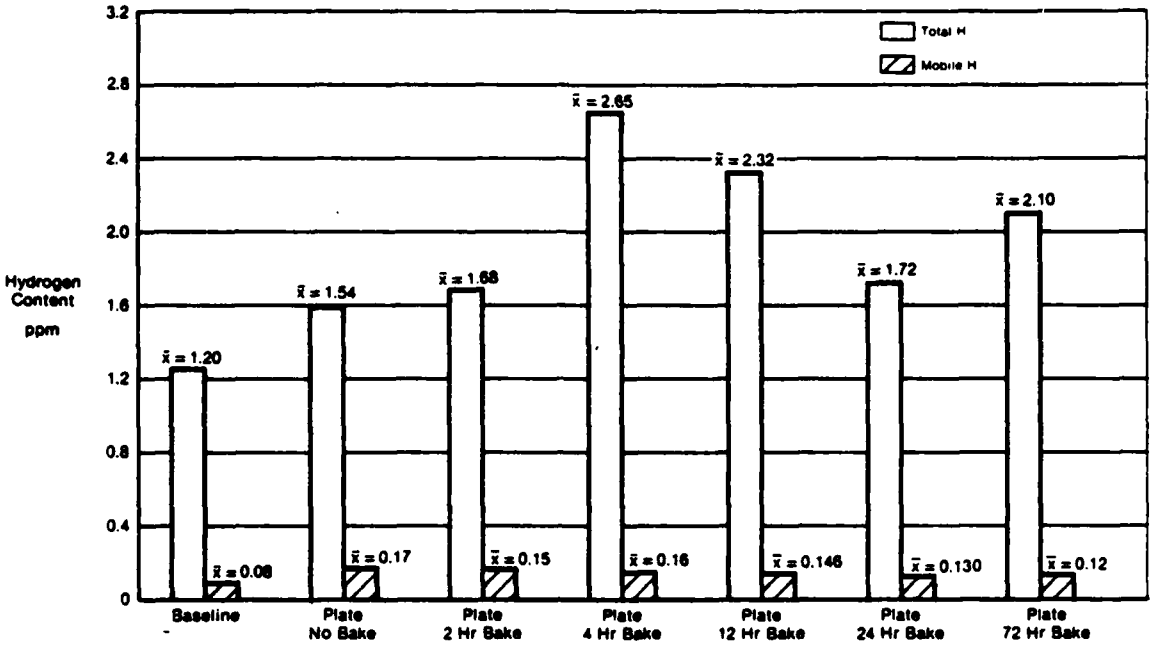


Figure 6. Total and Mobile Hydrogen in Cadmium Plated and Baked 4340 Steel

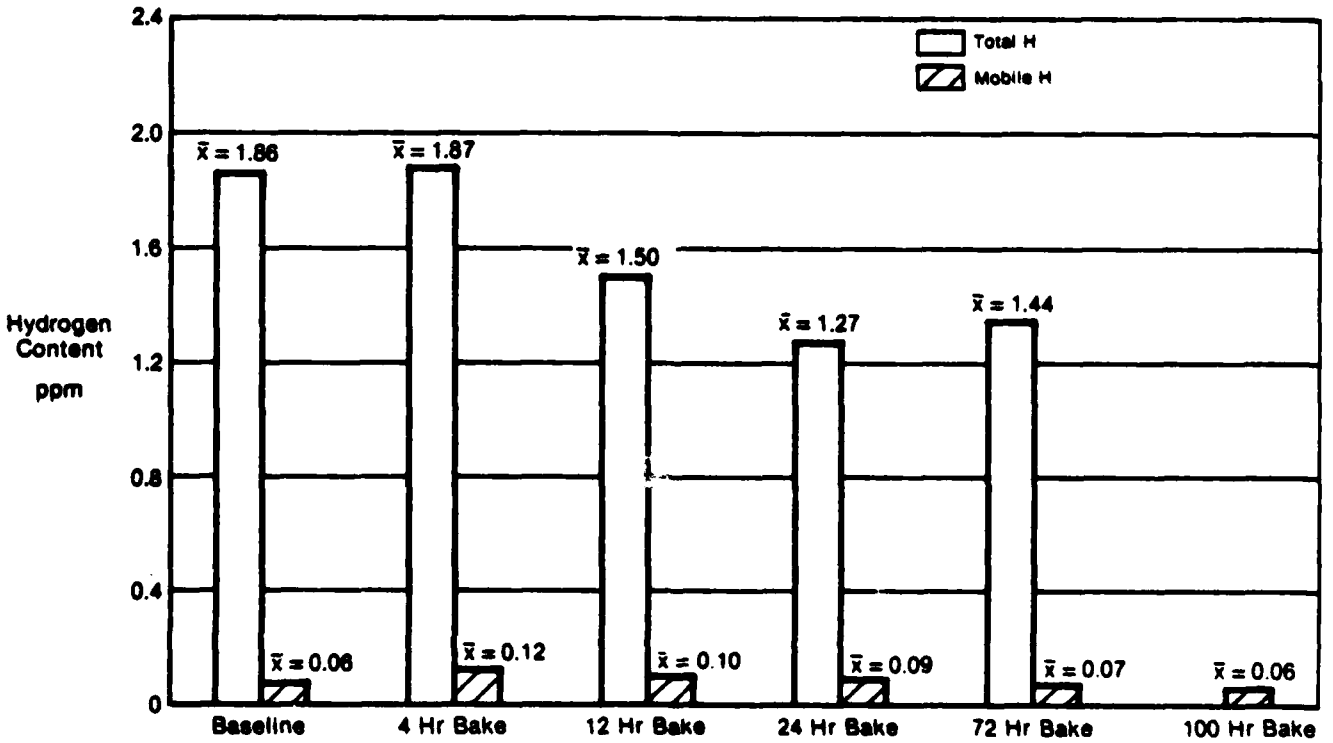


Figure 7. Total and Mobile Hydrogen in Cadmium Plated and Baked 300M Steel

The baseline (unplated) 200 hour safe life was determined first. The specimens were loaded to obtain a stress which was expressed as a percentage of its notch tensile strength. The load was adjusted upward or downward by 5% depending on whether the specimen failed or passed the 200 hour test. In most cases, duplicate tests were run at a specific load to verify the passing load.

This procedure was then repeated for each lot of plated specimens. The results of the 200 hour NSR tests are contained in Tables 5 and 6 and plotted as a function of the average BE reading for that lot in Figures 8 and 9 for the 4340 and 300M steels, respectively. These figures contain only the data showing the highest values (% of NTS) for which a 200 hour safe life was determined.

TABLE 5

NOTCH STRESS RUPTURE LIFE OF AISI 4340 STEEL

CONDITION	LOAD %NTS	FAILURE TIME, HR
Baseline - No Plate	70	200
	90	200, 200, 200
	95	54
Plate - No Bake	15	200, 200, 200
	20	61
	25	12
Plate - 2 HR Bake	15	200
	20	200
	25	3,4
Plate - 4 HR Bake	15	200
	20	200, 11,45,61
	25	6
	35	16
Plate - 12 HR Bake	20	200
	25	24
	35	21
	40	20
Plate - 24 HR Bake	25	27
	30	200, 18
	35	10
	40	22
Plate - 72 HR Bake	45	200
	50	39,96
	55	28
	60	30,165
	70	0
	80	0

TABLE 6

NOTCH STRESS RUPTURE LIFE OF 300M STEEL

CONDITION	LOAD %NTS	FAILURE TIME, HR
Baseline - No Plate	70	200
	80	200
	90	200
	95	60
Plate - 4 HR Bake	20	200, 200
	25	10
	30	13
Plate - 12 HR Bake	20	200, 200
	25	13
	30	11
Plate - 24 HR Bake	20	200, 200
	25	10
	30	22
Plate - 72 HR Bake	40	132
	45	10,18
	50	38
	55	86
Plate - 100 HR Bake	65	200
	70	160,197

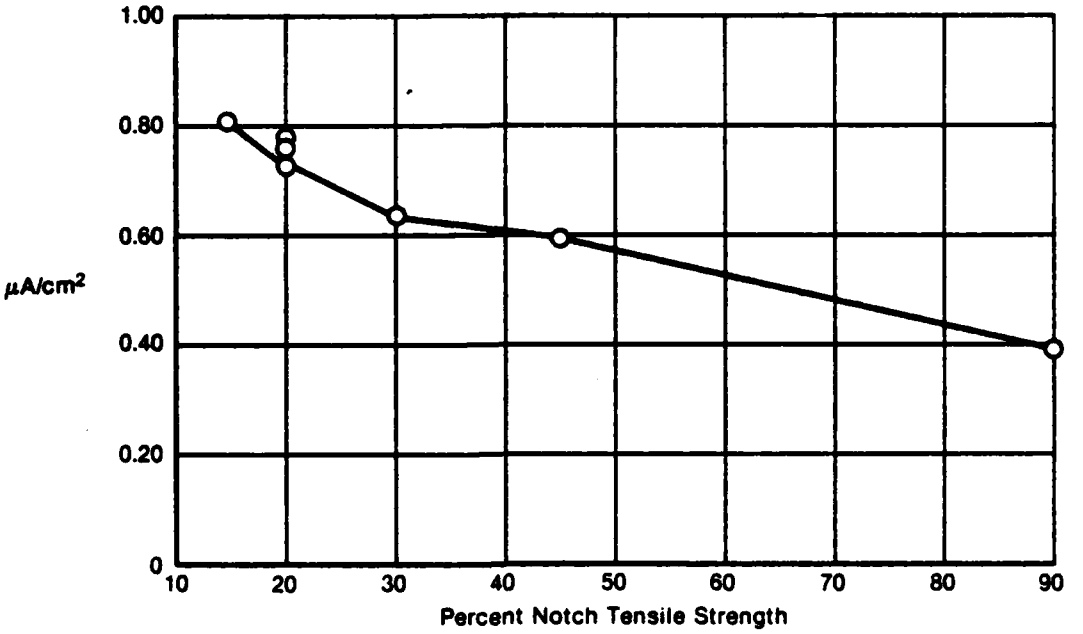


Figure 8. Effect of Mobile Hydrogen on the 200 Hour Notch Stress Rupture Strength AISI 4340 Steel

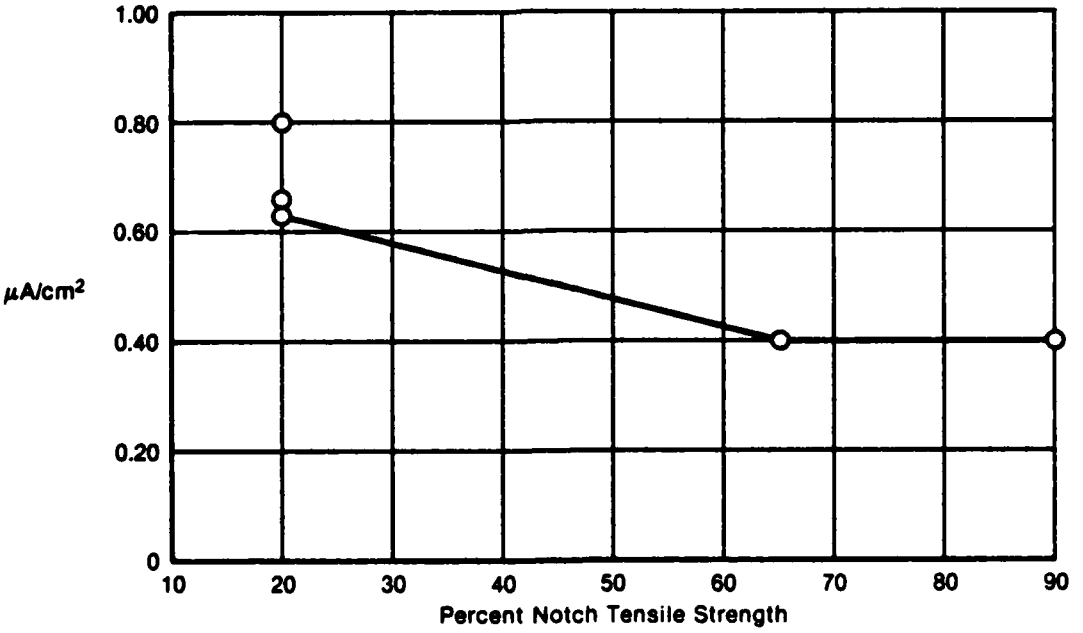


Figure 9. Effect of Mobile Hydrogen on the 200 Hour Notch Stress Rupture Strength 300M Steel

For bake cycles of 24 hours or less, the threshold stress to pass the 200 hour safe life was only 15% to 20% of the notch tensile strength indicating a high level of embrittlement. The first major improvement in threshold stress was after the 72 hour bake cycle for the 4340 steel where the threshold stress was 45% of its notch tensile strength. Erratic behavior in notch stress rupture life prevented determination of the safe life after a 72 hour bake for the 300M specimens. However, for this steel, the threshold stress for the 200 hour safe life after a 100 hour bake was determined to be 65% of its NTS.

3.4 TASK 4 - DATA ANALYSIS - The results of this study show that measurement of mobile hydrogen was a better indicator of hydrogen embrittlement (HE) than the measurement of total hydrogen. This can be seen in the plots (Figures 6 and 7) of total and mobile hydrogen. There was no definite pattern in the amount of total hydrogen as a function of bake time whereas the BE readings showed a trend of lower mobile hydrogen with increasing amount of bake time. The correlation of BE readings with 200 hour notch stress rupture life could be made whereas the erratic behavior of total hydrogen measurements precluded such a correlation.

A significant finding of this study is that baking times at 375°F (190°C) up to 72 hours do not restore the BE readings and the load carrying capability (% of NTS) to their baseline values of the AISI 4340 steel. This confirms the findings of Reference 6 in which it was found that bake times at 375°F (190°C) of over 100 hours would be required to restore baseline values in bright cadmium plated high strength steel.

The baseline values of BE readings are seemingly restored for 300M steel after a 100 hour bake but the threshold stress for the 200 hour NSR safe life was not. Our baseline values are higher than that reported by Berman (Reference 6). The reason for the higher values obtained in this study could not be determined. Incipient corrosion affecting the surface and near-surface layers of the specimen may have occurred during the period of specimen storage although evidence of such corrosion was not detected.

In this investigation, the effects of short baking times were studied where the concentration of mobile hydrogen was at or near saturation. A similar study using longer baking times, extending from 24 to 144 hours or longer, would have delineated the effect of mobile hydrogen on 200 hour notch stress rupture life more clearly.

The most damaging argument against reliance on measurement of total hydrogen as indicator of HE is found in data shown in Figure 7 (300M steel). The baseline hydrogen values are higher than those after plating and baking. These baseline specimens passed the 200 hour NSR test at 90% of NTS whereas the specimens supposedly showing a lower total hydrogen after a 24 hour bake were capable of passing the NSR test at only 20% of NTS. This indicates that measurement of total hydrogen can be seriously misleading in its determination of relative susceptibility to HE.

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4.0 CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

- The barnacle electrode can be used effectively to measure mobile hydrogen.
- The susceptibility to delayed failure can be correlated with levels of mobile hydrogen as measured by the barnacle electrode.
- Total hydrogen content determined by the inert gas fusion method is not a good indication of susceptibility to delayed failure.

RECOMMENDATIONS

- The cause for variation of barnacle electrode readings within a specimen and between specimens should be determined to improve its accuracy in predicting susceptibility to delayed failure.
- Additional work is recommended to index barnacle electrode readings to the degree of embrittlement of AISI 4340 and 300M steels to determine the effect of strength level and heat-to-heat compositional variations.
- A trial program should be initiated to use the barnacle electrode as a quality assurance tool in conjunction with the existing notch stress rupture requirements of MIL-S-5002. This combined testing would establish a data base for the correlation of the two test methods. A positive correlation will provide the basis for the confident use of the BE for monitoring susceptibility to hydrogen embrittlement in production parts thus eliminating the costly mechanical testing currently being employed.

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APPENDIX A

BARNACLE ELECTRODE AND INERT GAS FUSION DATA

TABLE A1. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

UNPLATED - BASELINE

AISI 4340 STEEL

Barnacle Electrode Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
B1	0.48, 0.32, 0.45, 0.36, 0.53	0.43
B2	0.37, 0.38	0.38
B3	0.33, 0.34, 0.47	0.38
B5	0.36, 0.55	0.46
B6	0.31, 0.38, 0.32	0.34
B7	0.33, 0.29, 0.27	0.30
B8	0.35, 0.48, 0.48	0.44
B9	0.35, 0.36, 0.26, 0.43	0.35
B10	0.33, 0.40, 0.43	0.39
B11	0.36	0.36
S11	0.37, 0.41, 0.39	0.39
S12	0.35, 0.32, 0.34	0.34
S13	0.46, 0.61, 0.53	0.53
S15	0.29, 0.43, 0.40	0.37
S16	0.32, 0.41, 0.31, 0.33	0.34
S17	0.30, 0.46, 0.38	0.38
S18	0.28, 0.40, 0.35	0.34
S19	0.38, 0.40, 0.35	0.38
S21	0.36, 0.37, 0.35	0.35
S22	0.30, 0.50, 0.39	0.40
S23	0.51, 0.53, 0.41, 0.53	0.50
S28	0.44, 0.41, 0.44	0.43
S32	0.52, 0.51, 0.39	0.47

$\bar{x} = 0.39 \ \mu A/cm^2$
$s = 0.06$
$n = 23$

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
B1	1.47, 1.55, 1.16, 1.49, 1.33	1.46
B3	1.57, 0.97, 1.03	1.19
B6	1.07, 0.93, 0.81	0.94

Average, 1.20 ppm

TABLE A2. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND NOT BAKED

AISI 4340 STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
B2	0.65, 0.81, 1.08, 0.75, 0.69	0.80
B4	0.89, 0.90, 0.88	0.89
B6	0.62, 0.74, 0.69	0.68
S16	0.99, 0.95	0.97
S17	1.03, 0.81, 0.85	0.90
S18	0.64, 0.75, 0.75	0.71

$\bar{x} = 0.83\ \mu A/cm^2$
$s = 0.11$
$n = 6$

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
B5	1.52, 1.52, 1.26	1.43
B6	1.48, 1.57, 1.62	1.56

Average, 1.54 ppm

TABLE A3. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND 2 HOUR BAKE

AISI 4340 STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
B7	0.74, 0.68, 0.82, 0.82, 0.67, 0.78	0.75
S21	0.78, 0.75, 0.73	0.73
S23	0.80, 0.60, 0.71	0.70
S26	0.73, 1.03	0.88

$\bar{x} = 0.76\ \mu A/cm^2$
$s = 0.08\ \mu A/cm^2$
$n = 5$

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
B7	1.83, 1.56, 1.66	1.68

TABLE A4. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND 4 HOUR BAKE

AISI 4340 STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
B8	0.65, 0.63, 0.74	0.67
B10	0.67, 0.77, 0.62	0.69
S28	1.07, 0.73, 0.92	0.91
S29	0.86, 0.70, 1.16	0.91
S30	0.76, 1.29, 1.50, 0.62	1.04
S33	0.66, 0.52, 0.63, 0.55	0.59
S34	0.74, 0.66, 0.54, 0.59	0.63

$\bar{x} = 0.78\ \mu A/cm^2$
$s = 0.17\ \mu A/cm^2$
$n = 7$

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
B8	2.27, 3.62, 2.05	2.65

TABLE A5. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND 12 HOUR BAKE

AISI 4340 STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
B9	0.95, 0.72, 0.79, 0.80	0.82
S35	0.67, 0.95, 0.76	0.79
S36	0.56, 0.70, 0.72, 0.58	0.64
S37	0.68, 0.84, 0.65	0.72
S38	0.73, 0.84, 0.60, 0.67	0.71

$\bar{x} = 0.74\ \mu A/cm^2$
$s = 0.07\ \mu A/cm^2$
$n = 5$

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
B9	2.56, 2.35, 2.06	2.32

TABLE A6. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND 24 HOUR BAKE

AISI 4340 STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
B12	0.54, 0.62, 0.55	0.57
S40	0.44, 0.51	0.48
S41	0.77, 0.88, 0.66	0.77
S42	0.50, 0.65, 0.59	0.58
S43	0.82, 0.65, 0.55	0.67
S44	0.67, 0.74	0.70

$\bar{x} = 0.63\ \mu A/cm^2$
$s = 0.10\ \mu A/cm^2$
$n = 6$

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
B12	1.70, 1.89, 1.56	1.72

TABLE A7. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND 72 HOUR BAKE

AISI 4340 STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
B13	0.66, 0.54, 0.62	0.61
S45	0.62, 0.60, 0.55	0.59
S46	0.66, 0.72, 0.73	0.70
S47	0.46, 0.44, 0.54	0.48

$\bar{x}$ = 0.60 $\mu A/cm^2$
s = 0.09 $\mu A/cm^2$
n = 4

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
B13	1.88, 2.32	2.1

TABLE A8. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

BASELINE 300M STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
BM1	0.29, 0.34, 0.43	0.35
BM2	0.37, 0.36	0.36
BM3	0.42, 0.46, 0.42	0.43
BM6	0.34, 0.45, 0.40	0.40
SM11	0.36, 0.40, 0.35	0.37
SM12	0.36, 0.44, 0.48	0.43
SM13	0.47, 0.45, 0.42	0.45
SM16	0.34, 0.37	0.36
SM17	0.42, 0.37	0.40
SM18	0.42, 0.44	0.43
SM21	0.30, 0.31, 0.44	0.35
SM22	0.42, 0.56, 0.50	0.49
SM25	0.29, 0.42, 0.41	0.37
SM26	0.34, 0.47, 0.33	0.38
SM31	0.42, 0.59	0.51

$\bar{x} = 0.41$
$s = 0.05$
$n = 15$

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
BM1	1.86, 2.10	1.98
BM2	1.64, 1.83	1.74

Average, 1.86 ppm

TABLE A9. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND 4 HOUR BAKE

300M STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
BM4	0.76, 0.91, 0.76	0.81
SM23	0.68, 0.67, 0.62	0.66
SM24	0.87, 0.90, 0.89	0.89
SM25	0.96, 0.79, 0.82, 0.82	0.85

$\bar{x} = 0.80\ \mu A/cm^2$
$s = 0.10\ \mu A/cm^2$
$n = 4$

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
BM4	1.80, 1.85, 1.95	1.87

TABLE A10. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND 12 HOUR BAKE

300M STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
BM5	0.67, 0.63, 0.61	0.64
SM26	0.97, 0.92, 0.72	0.87
SM27	0.68	0.68
SM29	0.63, 0.55, 0.44	0.54
SM30	0.57, 0.56, 0.61	0.58

$\bar{x} = 0.66\ \mu A/cm^2$
$s = 0.13\ \mu A/cm^2$
$n = 5$

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
BM5	1.33, 1.85, 1.33	1.50

TABLE A11. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND 24 HOUR BAKE

300M STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
BM6	0.69, 0.64	0.67
SM32	0.58, 0.61, 0.46	0.55
SM33	0.55, 0.69, 0.64	0.63
SM34	0.59, 0.76, 0.69	0.68

$\bar{x} = 0.63\ \mu A/cm^2$
$s = 0.06\ \mu A/cm^2$
$n = 4$

Total Hydrogen Content

Specimen No.	*Hydrogen* Content, ppm.	Specimen Average ppm
BM6	1.36, 1.18	1.27

TABLE A12. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND 72 HOUR BAKE

300M STEEL

Barnacle Readings

Specimen No.	BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
BM7	0.39, 0.34, 0.38	0.37
SM36	0.55, 0.42, 0.43	0.47
SM37	0.43, 0.54, 0.55	0.51
SM38	0.49, 0.49, 0.55	0.51
SM39	0.49, 0.47, 0.45	0.47
SM40	0.55, 0.56	0.56

$\bar{x} = 0.48\ \mu A/cm^2$
$s = 0.06\ \mu A/cm^2$
$n = 6$

Total Hydrogen Content

Specimen No.	Hydrogen Content, ppm.	Specimen Average ppm
BM7	1.24, 1.63	1.44

TABLE A13. BARNACLE ELECTRODE READINGS AND TOTAL HYDROGEN CONTENT

CADMIUM PLATED AND 100 HOUR BAKE

300M STEEL

Specimen No.	Barnacle Readings BE Reading $\mu A/cm^2$	Specimen Average $\mu A/cm^2$
41	0.49, 0.46, 0.39, 0.37	0.43
42	0.62,* 0.37	0.37
43	0.35	0.35

$\bar{x} = 0.38\ \mu A/cm^2$
$s = 0.04\ \mu A/cm^2$
$n = 3$

*Not included in average

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